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"Femto-Second Pulses of Synchrotron Radiation"

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Femto-Second Pulses of Synchrotron Radiation*

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Abstract

A method capable of producing femto-second pulses of synchrotron radiation is proposed. It is based on the interaction of femto-second light pulses with electrons in a storage ring. The application of the method to the generation of ultra-short x-ray pulses at the Advance Light Source of Lawrence Berkeley National Laboratory has been considered. The same method can also be used for extraction of electrons from a storage ring in ultra-short series of microbunches spaced by the periodicity of light wavelength.

I. DESCRIPTION OF THE METHOD

In this paper we consider a method for the generation of femto-second pulses of synchrotron radiation by electrons in a storage ring. For such a short duration of the radiation pulses we must use synchrotron radiation of electrons only from a thin slice of the bunch. How to separate the radiation of these electrons from the radiation of all other electrons? A method that we will discuss here consists in a positioning of electrons from a thin slice of the electron bunch aside from the beam core and isolating their synchrotron radiation by means of collimation of synchrotron radiation from beam core electrons.

How to induce transverse off-set of electrons only in a thin slice of a bunch and do not affect other electrons? We found that existing lasers allow us to do this. Indeed, femto-second laser pulses can be used for modulation of electron's energies within a thin slice of the bunch. Due to the high electric field possible in the ultra-short light pulse, the amplitude of this energy modulation can be several times larger than the r.m.s. beam energy spread. Then, this energy modulation can be transformed into the modulation of electron's transverse coordinates with an amplitude, which will also be much larger than the r.m.s. transverse size of a beam. Finally, by a collimation of the synchrotron radiation of electrons in the beam core we will get pulses of synchrotron radiation only from the off-set electrons with approximately the same duration as a duration of the light pulses.

The process for the generation of femto-second pulses of synchrotron radiation is schematically shown in the Figure 1. Electrons circulate in a storage ring and interact with the light in an undulator where they oscillate within the envelope of the light beam. This interaction produces the modulation of electron's energies. The energy of the light pulse, required for a modulation of electron's energies with the modulation amplitude p times larger than the r.m.s. beam energy spread, can be estimated as follows:

$$A \simeq p^2 \sigma_e^2 mc^2 \frac{\sigma_\tau c}{4\pi r_0 M} \gamma^2 \qquad (1)$$

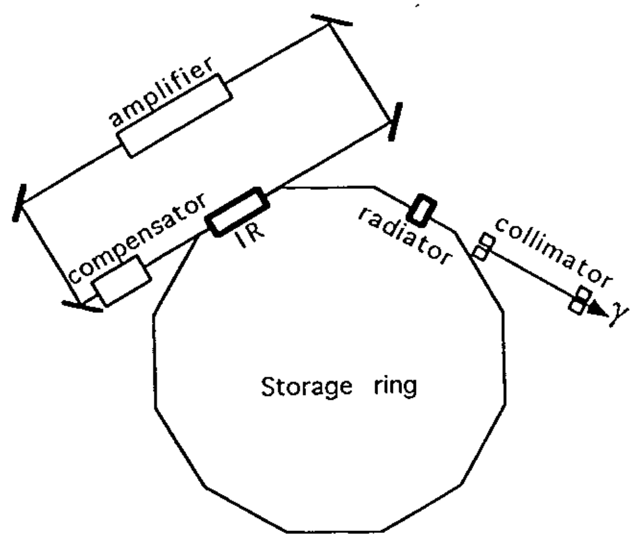

Figure. 1. Schematic of the generation of the femto-second pulses of synchrotron radiation.

Here m and r_0 are rest mass and classical radius of the electron, c is the speed of the light, γ is the Lorentz factor, σ_τ is a duration of the light pulse, σ_e is the r.m.s. relative beam energy spread, M is the number of undulator periods and A is the energy of the light pulse. Notice, that M in Eq.(1) has an optimal value. When $M \simeq 2\sqrt{2\pi}\sigma_\tau c/\lambda_L$, where λ_L is the light wavelength, then electrons within a bunch slice of length $\sqrt{2\pi}\sigma_\tau c$ entering the undulator ahead of the light pulse will slip over the entire light pulse during the passage of the undulator, thus fully utilizing the light pulse. Further increase of M can only make the electron bunch slice longer, but will not lead to a higher energy modulation amplitude. Contrary, a reduction of M will have an effect of decreasing of the energy modulation amplitude. It is worth mentioning here that in average there is no net energy transfer from the light to the electron beam.

The whole interaction region (IR) of electrons with the light pulse is placed in one shoulder of the optical cavity. This cavity is used in order to enhance the utilization of the laser beam. Therefore, it also includes an optical amplifier and a pulse stretching compensator.

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Transverse separation of electron's orbits naturally occurs when an energy modulated bunch slice proceeds into a region with a non-zero dispersion function induced by the bending magnets following the IR. With a large amplitude of electron's energy modulation we can reach a condition when a population of electrons at large transverse coordinates is dominated by the electrons from a bunch slice involved into the interaction with the light.

Synchrotron radiation is emitted in the radiator which can be either an undulator or a bending magnet. The actual choice depends from the application. (We assume that the radiator is optimized to provide the maximum yield of the synchrotron radiation in a given spectral range).

The last element in the scheme is a collimator, which is, basically, a set of two synchrotron radiation masks. One mask is placed in a position nearest to the electron beam (preferably inside the vacuum chamber) and one mask is placed in front of the experimental area. Both masks block synchrotron radiation of the beam core electrons and have two narrow windows to allow for synchrotron radiation of the off-set electrons to propagate to the experimental area. Thus, an observer behind the windows will see pulses of synchrotron radiation with a high intensity peak of a duration σ_τ on a top of a low intensity pedestal of a duration σ_z/c, where σ_z is the bunchlength.

II. INTENSITY AND BRIGHTNESS

The number of electrons per second involved in the interaction with the light pulses is $N_b f_L \sigma_\tau c/\sigma_z$, where N_b is the number of bunch electrons and f_L is the frequency of interactions with the light pulses. Only a fraction of these electrons interacts with the light near the optimal phase of the electric field oscillations and gets energy kicks, suitable for creating the large transverse off-sets. We will define this fraction with a symbol η. (An explicit expression for η will be given in the example.)

There are two main factors imposing a limit on f_L and, accordingly, on the average intensity of femto-second radiation. One factor is related to the storage ring and one factor is related to the laser.

As for the storage ring, the limitation arises due to the growth of the beam energy spread in the following process. Each time the electron bunch interacts with the light pulse a large fraction of electrons from a bunch slice involved in the interaction gets a strong energy kick. It is important for maintaining the stability of electron motion in a storage ring that the next time, when the same electron bunch interacts with the light, new electrons are kicked. If this condition is satisfied, then energy kicks can be considered as random leading to a diffusion of the beam energy spread with a growth time τ_g defined as

$$\frac{1}{\tau_g} = \frac{p^2 \sigma_\tau c}{2\sigma_z} \frac{f_L}{n}, \tag{2}$$

where n is the number of bunches. Synchrotron radiation damping will regulate energy growth such that the equilibrium energy spread will be settled at the following value:

$$\sigma_e^2 = \frac{\sigma_{e0}^2}{1-(p^2\sigma_\tau c/2n\sigma_z)\tau f_L}, \tag{3}$$

where σ_{e0} is the beam energy spread in the storage ring without beam interaction with light pulses and τ is the damping time.

How long would it take for a randomization of the electrons that once appeared all together in one slice? If it is less then one period of the same bunch interaction with light, then the light pulse can always be applied to the central slice of the bunch. If it is more than one period, then we can make the light pulse to interact with different bunch slices.

At this point we should mention that the limitation we just described is not inevitable and could be overcome in a more elaborate scheme. In fact, let us consider two identical places in a storage ring (one downstream to another with a radiator in between) where electron beam interacts with the light. Providing an isochronous beamline between these places and adjusting the relative phase between optical cavities to 180° one gets a condition when energy modulation of electrons appeared in the first cavity is canceled in the second cavity. Since energy losses in the radiator are small, the remaining effects associated with them are also small. Thus, a growth of the beam energy spread can be eliminated.

Now, assuming that Eq.(3) defines a maximum energy spread acceptable for a normal machine operation, we can find the maximum acceptable f_L and a flux of photons radiated by $\eta N_b \sigma_\tau c/\sigma_z$ electrons in the bending magnet from a segment of the circular trajectory with the azimuthal angle $\delta\theta$ in the bandwidth $\Delta\lambda/\lambda$ [1]:

$$\mathcal{F}(\lambda) = \frac{\sqrt{3}}{\pi}\alpha\,\gamma\,\delta\theta\frac{\eta I}{p^2 e f_0 \tau}\left[1-\left(\frac{\sigma_{e0}}{\sigma_e}\right)^2\right] F(\frac{\lambda_c}{\lambda})\frac{\Delta\lambda}{\lambda} \tag{4}$$

Here $\mathcal{F}$ is the photon flux (number of photons per second), α is the fine structure constant, I is the average beam current, e is the electron charge, f_0 is the revolution frequency λ_c is the critical wavelength of radiation and F is the spectral function: $F(y) = y\int_y^\infty K_{5/3}(\xi)\,d\xi$, where $K_{5/3}$ is the modified Bessel function of the second kind. (For an undulator radiation one can get very similar expression.)

Consider now the limit on the average intensity of the femto-second radiation caused by the laser. The available output power of the optical amplifier, P_L, and the quality factor of the optical cavity, Q, define the reactive power in the optical cavity. Then, for a given A the maximum interaction frequency is $f_L = P_L Q/A$. If this frequency is less than f_L defined by the growth of the beam energy spread, then

$$\mathcal{F}(\lambda) = \frac{\sqrt{3}}{2\pi}\alpha\,\gamma\,\delta\theta\frac{\eta I}{n e f_0}\frac{\sigma_\tau c}{\sigma_z}\frac{P_L Q}{A}F(\frac{\lambda_c}{\lambda})\frac{\Delta\lambda}{\lambda} \tag{5}$$

and the beam energy spread in the Eq.(3) must be evaluated with the actual f_L.

Brightness of the source of the radiation as it is defined in [2] can be find as follows:

$$\mathcal{B} = \frac{d^4\mathcal{F}}{dxdyd\theta dy'} = \frac{\mathcal{F}}{(2\pi)^{3/2}\,\sigma_x\epsilon_y\delta\theta} \qquad (6)$$

III. PULSE DURATION LIMIT

What is the minimum duration of the synchrotron radiation pulses that is achievable with the above described technique? Of course, it is defined by the light pulse shape and by the number of undulator periods M, but on top of this there will be stretching of the electron bunch slice on the way from the IR to the radiator and in the radiator. This process is related to the non isochronisity of the beamline and can be characterized by the differences of the pathlengths of electron trajectories [3]:

$$\Delta\ell = \left[I_U^2\sigma_x^2 + I_V^2\sigma_{x'}^2 + I_D^2\sigma_e^2\right]^{1/2}, \qquad (7)$$

where $\Delta\ell$ is the r.m.s. spread of the pathlengths, σ_x and $\sigma_{x'}$ are the horizontal beam size and divergence of the electron beam in the IR, $I_U = \int_0^\ell \frac{U(z)}{\rho}dz$, $I_V = \int_0^\ell \frac{V(z)}{\rho}dz$, $I_D = \int_0^\ell \frac{D_x(z)}{\rho}dz$, U and V are two independent cosine-like and sine-like solutions of the homogeneous equation of the electron motion, D_x is the dispersion function, ρ is the bending radius and ℓ is the distance from the IR to the radiator.

Although, I_D can be zero in a specially designed beamline, a fully isochronous lattice between the IR and the radiator is impossible. Either I_U or I_V must be non zero as a result of a creation of the dispersion function on the way from the IR to the radiator [3]. A value $\Delta\ell$ associated with that can be estimated as follows:

$$\Delta\ell \simeq \frac{\epsilon_x}{\sigma_e}, \qquad (8)$$

where ϵ_x is the horizontal beam emittance.

Notice, that the pulse stretching with the vertical dispersion in the radiator will be much smaller than with the horizontal dispersion, since it will then be defined by the vertical beam emittance, which is much smaller than the horizontal emittance in the storage rings.

IV. SIGNAL AND BACKGROUND

We define a background as the synchrotron radiation propagated to the experimental area through the windows of the collimator and emitted by the electrons which do not belong to the bunch slice involved into the interaction with the light. If bunch frequency is larger than the frequency of the light pulses, then gated input, triggered with the light pulse frequency, should be used to keep the background low. Then, a signal-to-background ratio, $\mathcal{R}$, will be a ratio of the intensity of the synchrotron radiation integrated over the femto-second pulse to the intensity of the synchrotron radiation integrated over the bunchlength except the femto-second pulse.

Table I
Summary of the ALS beam parameters

Beam energy	E [GeV]	1.5
Revolution frequency	f_0 [MHz]	1.5
Total beam current	I [A]	0.4
Number of bunches	n	40
Damping time	τ [ms]	10.7
Energy spread	σ_{e0}	8×10^{-4}
Bunch length	σ_z [cm]	0.4
Horizontal emittance	ϵ_x [nm×rad]	4
Vertical emittance	ϵ_y [nm×rad]	0.1
	Beam parameters in the radiator	
Total horizontal beam size	σ_x [mm]	0.13
Dispersion function	D_x [m]	0.13
Dispersive beam size	σ_{xs} [mm]	0.10
	Beam parameters in the IR	
Horizontal beam size	σ_x [mm]	0.2
Horizontal divergence	$\sigma_{x'}$ [mrad]	2×10^{-2}
Dispersion function	D_x [m]	0

Electrons contributing to the background radiation are the electrons that appeared in the transverse beam tails due to the natural distribution of the beam particle density. Therefore, better $\mathcal{R}$ correspond to conditions with larger off-sets of electrons in the bunch slice and, correspondently, larger amplitudes of the energy modulation of electrons by the light. But, larger modulation amplitudes correspond to the lower flux of the femto-second radiation. (Notice, that $\mathcal{F} \sim 1/p^2$ as follows from Eq.(4) and Eq.(5)). Therefore, the actual value of the modulation amplitude must be adjusted depending upon the tolerance to the background in the experiment utilizing the femto-second synchrotron radiation.

V. EXAMPLE

For illustration of the above described technique, consider the application to the generation of femto-second x-ray pulses at the Advance Light Source of Lawrence Berkeley National Laboratory [4]. Beam parameters for this storage ring are listed in the Table I.

As a source of the radiation consider a superconducting bending magnet with 5 T magnetic field currently under development for the ALS [5]. The critical wavelength of the synchrotron radiation in this magnet at 1.5 GeV is 1.6 Å and we assume that x-rays of this wavelength will be used in the experiments.

Assume that undulator W16 which will soon be installed in the ALS will be used to provide interactions of electrons with the light. This undulator has 19 periods, period length $\lambda_u = 16$ cm and adjustable undulator parameter K in the range of $K = 1 \div 30$ [6]. (We need $K \simeq 11.5$ for a first harmonic radiation in the undulator at $\lambda_L = 0.6\mu$m; $\lambda_L = \lambda_u\left(1 + K^2/2\right)/2\gamma^2$ [2]).

For a duration of the light pulses assume the FWHM duration of 50 fs. It is approximately two and a half times longer than the optimal duration related to the number of periods in the undulator.

Suppose that the amplitude of electron's energy modulation produced in the interaction with the light is four and a half times bigger than equilibrium energy spread, i.e. $p = 4.5$.

Consider the upper limit for a growth of the beam energy spread being $\sigma_e/\sigma_{e0} = 1.5$.

Then we calculate:

- $A = 180\,\mu$J
- $f_L = 135$ kHz

For collimators we assume setting, that leaves open the window for synchrotron radiation originated in the arc with a sagitta equal to σ_x. Then we calculate:

$$\delta\theta = \sqrt{\frac{8\sigma_x}{\rho}} \simeq 30\,\mathrm{mrad}, \tag{9}$$

(ρ is the bending radius of the superconducting magnet)

$$\eta = \frac{1}{\pi}\cos^{-1}\left(1 - \frac{\sigma_x}{2p\sigma_{xs}}\right) \simeq 0.15 \tag{10}$$

and signal-to-background ratio

$$\mathcal{R} = \frac{2\eta\sigma_\tau c}{\sigma_z}\left[\Phi\left(\frac{p\sigma_{xs}}{\sigma_x} + \frac{1}{2}\right) - \Phi\left(\frac{p\sigma_{xs}}{\sigma_x} - \frac{1}{2}\right)\right]^{-1} \simeq 2, \tag{11}$$

where Φ is the error function and the Gaussian particle density distribution is implied.

Finally, with all the above defined parameters we find:

- $\mathcal{F} = 2\times 10^{11}\Delta\lambda/\lambda$ x-rays/sec
- $\mathcal{B} = 3.5\times 10^{13}\,\mathrm{mm}^{-2}\mathrm{mrad}^{-2}\mathrm{sec}^{-1}$ in 0.1 % bandwidth.

For a pulse duration calculation we must know I_U, I_V and I_D. In the ALS they are -0.012, -0.39 m and -0.0045 m correspondently. Therefore, stretching of the electron bunch slice, occurred on the way from the IR to the radiator is $\Delta\ell \simeq 10\,\mu$m. Thus, the r.m.s. duration of the x-ray pulses is

$$\sigma_{x-ray} = \sqrt{\sigma_\tau^2 + (\Delta\ell/c)^2} \simeq 40\,\mathrm{fs} \tag{12}$$

VI. HIGH FREQUENCY CHOPPER

It turns out that the above described method is also suitable for an extraction of electrons from a storage ring in ultra-short series of microbunches with a well defined period. In fact, assume, that there is a septum magnet instead of the radiator in a region of a high dispersion function. Then, electrons with a large energy deviation ($p \simeq 10$) from the equilibrium energy can be shifted into the septum. Of course, only electrons which were grouped around the optimal phase of the electric field in the IR will get substantial energy kicks to be shifted into the septum. (We will call such groups of electrons as microbunches because they are much shorter than the light wavelength). Other electrons will stay inside the main storage ring vacuum chamber or will fall onto the septum knife. As we know, electrons that were within one microbunch in the IR do not remain there when they appear in the septum (due to non isochronisity of the lattice between the IR and septum). But, temporal structure of microbunches can be restored after the septum in the extraction beamline. Since only microbunches are extracted, then at the end of the extraction beamline we can get a train of microbunches of electrons separated on λ_L. The overall duration of the electron macropulse will be the same short as the duration of the light pulse.

VII. CONCLUSION

We have shown the method to generate femto-second pulses of the synchrotron radiation. The method involves the interaction of the electron beam with femto-second light pulses and substantially based on the availability of lasers capable to the high energy light pulses. The method fully utilizes a progress in the femto-second technique, currently achieved in the visible light spectrum, and allows its extension to a much broader spectral range accessible with the synchrotron radiation.

In the example we considered the generation of the femto-second x-ray pulses at the Advance Light Source. We have shown that the brightness of the source of the radiation in 0.1 % bandwidth in this storage ring can be $3.5\times 10^{13}\,\mathrm{mm}^{-2}\mathrm{mrad}^{-2}\mathrm{sec}^{-1}$ and that the r.m.s. duration of x-ray pulses can be 40 fs.

We also suggested that the same method can be used for an extraction of electrons from a storage ring in ultra-short series of microbunches spaced by the periodicity of a light wavelength.

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References

[1] Landau L.D., The classical theory of fields, Oxford, Pergamon Press, 1975.

[2] X-ray Data Booklet, PUB-490, LBL, p.4-2, 1986.

[3] K.Steffen, CAS CERN Accelerator School, CERN 90-03, 1990.

[4] 1-2 GeV Synchrotron Radiation Source, PUB-5172, LBL.

[5] C.Taylor, S. Caspi, A 6.3 T Bend Magnet for the Advance Light Source, LBL-37346, 1995.

[6] E.Hoyer, Engineering Note AL0741, LBL, 1995.